TROPOSPHERIC LIMITATIONS TO THE STABILITY OF RADIO METRIC DELAY MEASUREMENTS

Dr. R. N. Treuhaft
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Abstract

Fluctuations in the index of refraction in both the wet and dry components of the troposphere induce timing instabilities in radio metric data in excess of that of modern frequency standards. At zenith, the wet and dry tropospheres cause fluctuations of the order of 2×10^{-14} s/s and 7×10^{-15} s/s at 1000 seconds, respectively. A description of the temporal and spatial characteristics of the wet and dry troposphere is given based on frozen flow modelling. The level of the fluctuations at various time scales and elevations is presented along with calibration strategies being investigated for both the wet and dry components.

CHARACTERIZING TROPOSPHERIC FLUCTUATIONS

Wet and dry tropospheric fluctuations, of the order of 2×10^{-14} s/s and 7×10^{-15} s/s at 1000 seconds respectively, far exceed the temporal fluctuations of modern time standards in radio metric data. The tropospheric fluctuations can be characterized as a spatial pattern obeying Kolmogorov statistics[1], which is transported across a site by the wind. The results presented in this paper are based on a model which follows from that assumption[2]. The fluctuation modelling results show good agreement with wet tropospheric levels and spectral shapes. Dry fluctuation results presented here are an extension of the wet fluctuation model, with the parameters of wind speed, atmospheric height, and turbulence scale factor changed. The model has not yet been extensively compared to dry fluctuation data. Wet statistics were normalized by water vapor radiometer data from Goldstone, California[2] and dry statistics were normalized by barometric pressure fluctuation data also taken at Goldstone.

Viewing tropospheric fluctuations as arising from a frozen spatial pattern, which is blown across a site by the wind, allows an important connection between spatial and temporal fluctuation scales. For example, for a wind vector $\vec{V}$, a fluctuation lasting for T seconds corresponds to a spatial fluctuation of approximate dimension VT. Similarly, if radio metric delay is averaged over a time T, then only spatial features of the order of VT contribute to the observed average delay. Features much shorter than this scale average to zero, and features much larger than VT tend to vary slowly over the time interval T. For an interferometer of length L, tropospheric fluctuations on time scales smaller than L/V will not be correlated between the two ends of the interferometer; while fluctuations on time scales much greater than L/V will cause similar signatures at each end of the interferometer and

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will therefore largely cancel. Applications of the relation between spatial and temporal scales will be discussed in the section on calibration techniques.

THE LEVEL OF WET AND DRY FLUCTUATIONS

Figure 1 shows the Allan standard deviation of zenith wet and dry fluctuations, based on the frozen flow modelling mentioned above. At 1000 seconds, the wet and dry Allan standard deviations are approximately 2×10^{-14} s/s and 7×10^{-15} s/s respectively. These levels of instability are of the order of or exceed those of modern timing standards. Most statistics of the troposphere have the characteristic rollover seen around 100 seconds in Figure 1. This is typically referred to as the transition from three dimensional to two dimensional turbulence. This nomenclature arises from the fact that at short time periods, or high frequencies, turbulent cells smaller than the tropospheric scale height (1–2 km wet, 4–8 km dry) dominate. These cells can be equally large in any dimension, and can be regarded as statistically spherical. Moving to the right on the abscissa of Figure 1 is equivalent to sampling larger and larger spherical cells. At a time equal to about the tropospheric scale height over the wind speed, taken to be 8 m/s for the wet and 15 m/s for the dry, moving to the right on the abscissa no longer samples spherical features. The cells must become oblate as they "hit" the top of the troposphere. A qualitative explanation of the rollover is that, as the time interval increases, the oblate cells can no longer grow in the height dimension, and therefore the statistical fluctuation trend with time decreases slightly relative to that describing the spherical cells.

The elevation dependence of fluctuation statistics can also be qualitatively deduced from similar arguments. At short time scales, as the elevation angle decreases from zenith, more small fluctuation cells will be seen along the line of sight. Some cells will have an index of refraction higher than the mean, and some less. The net effect is to increase the fluctuation level proportional to the square root of the length of the raypath, or approximately proportional to $\frac{1}{\sqrt{\sin\theta}}$ where θ is the elevation angle. At time scales long compared to the scale height over the wind speed, as elevation decreases, one large feature is being sampled and the long-term statistics vary approximately as $\frac{1}{\sin\theta}$. The quantitative details supporting these arguments are in reference [2].

CALIBRATION STRATEGIES FOR WET AND DRY FLUCTUATIONS

The most promising means for reducing the effects of delay fluctuations due to water vapor is by the use of water vapor radiometers (WVR). While comparisons of WVR delays with radio metric delays have shown systematic differences over many-hour time scales[3], there is also data which suggest a high correlation between WVR and radio metric data over 1000-second time scales[4]. If the long-period systematics persist, it is possible that they can be removed by estimating tropospheric parameters from the radio metric data themselves. Because of the relation between spatial and temporal fluctuations, WVR's must be a distance no greater than VT from the antenna taking the radio metric data, in order to calibrate fluctuations over times greater than T. This is probably one of the reasons why direct WVR calibration has had mixed results, as the WVR's are usually within a few hundred meters of the primary antenna.

As indicated in Figure 1, if WVR's are successful at reducing the wet fluctuation level, the dry

fluctuations, which are about 1/3 as strong, will be the next tropospheric stability limitation. Three approaches are proposed here which could reduce the dry fluctuation level: 1) Global Positioning System (GPS) observations, 2) antenna arrays, 3) barometric arrays. The first two approaches could also be used to calibrate the wet component in the absence of WVR's. If all GPS errors besides the tropospheric contributions can be reduced on the time scale of interest, then GPS measurements near the line of sight of interest can be used to reduce the tropospheric contribution in other radio metric data. This technique could be used to calibrate both the wet and dry components, but, in the exercise that follows, it will be assumed that WVR's have completely removed the wet contribution from both the line of sight of interest and the lines of sight to the GPS satellites. A calculation has been done to determine the impact of the difference between the GPS and radio metric lines of sight. For both the primary line of sight of interest and the GPS raypath, assume an elevation angle of 20°. A single GPS satellite is assumed to be 20° away in azimuth from the line of sight of interest. Figure 2 shows the delay rate standard deviation for the uncalibrated dry delay along a line of sight at 20° elevation. The figure also shows the delay rate standard deviation for the difference between the uncalibrated line of sight and the delay measured along the GPS line of sight, 20° away in azimuth. The delay rate standard deviation is within about 30% of the Allan standard deviation and has the same approximate shape. A 4000–km scale height was assumed along with a wind speed of 15 m/s. It can be seen from the figure that the GPS calibration reduces the dry fluctuation level for time scales greater than about 200 seconds. Inferring the level of correlation of the two raypaths using the methods of described in the first section of this report yields a similar time scale. Naturally this result is based on a simplification of the real situation in which several GPS satellites are in view simultaneously with the line of sight of interest. This calculation is meant only to illustrate the potential of reducing the dry fluctuation level by observing a well–known beacon, such as the GPS, near the raypath of interest.

A second possible means of calibrating both wet and dry tropospheres is the use of antenna arrays. The frozen flow modelling again can be used to infer the utility of this approach. If a time scale T is of interest in a radio metric experiment, a second antenna located at a distance greater than VT away will experience tropospheric fluctuations which are uncorrelated with the first. The two signals from the antennas can later be averaged to reduce the effect of the fluctuation by a factor of $\sqrt{2}$. This argument can be extended to more than two antennas, and would therefore be applicable to experiments with the Very Large Array or arrays of GPS receivers. For time scales less than 40 minutes, multiple antennas within the Goldstone Deep Space Network complex could also be used to reduce the tropospheric fluctuation effects.

A possible approach for calibrating the dry delay is the use of barometric arrays. The dry zenith delay can be inferred from barometric pressure measurements. At lower elevations, atmospheric features as far as 20 kilometers from the antenna are being sampled due to the height of the troposphere. Using barometric arrays which sample the dry zenith delay at locations up to approximately 20 kilometers away may be useful in determining the dry fluctuations at low elevations. The measurement accuracy, modelling techniques, and spatial deployment necessary for barometric arraying to be effect have not been studied at the time of this report.

SUMMARY

Tropospheric fluctuations, both wet and dry, cause zenith delay fluctuations in radio metric measurements of the order 2×10^{-14} and 7×10^{-15} respectively at 1000 seconds. These fluctuations have been described in terms of a frozen flow model in which spatial index of refraction patterns are blown

across a site by the wind. For short time scales, fluctuation statistics are approximately proportional to $\frac{1}{\sqrt{\sin\theta}}$ where θ is the elevation angle. For long time scales, the statistics are approximately proportional to $\frac{1}{\sin\theta}$. The transition between "short" and "long" time scales takes place at about $\frac{h}{v}$, where v is the wind speed and h is the height of the troposphere. The most direct method for calibrating wet tropospheric delay fluctuations appears to be water vapor radiometry. Both the wet and dry delay could be calibrated by using a nearby GPS satellite raypath which, for sufficiently long time scales, will share the tropospheric signature of the raypath of interest. Results of a calculation were shown in which 20° elevation dry signatures could be reduced from 2×10^{-14} to 8×10^{-15} at 1000 seconds by a GPS raypath 20° from the raypath to be calibrated. Signals from additional receving antennas located at distances greater than VT from the primary antenna can be used to calibrate wet and dry tropospheres for time scales less than T. Obtaining barometric pressure readings at multiple sites surrounding the receiving antenna is another proposed method for reducing dry fluctuation effects.

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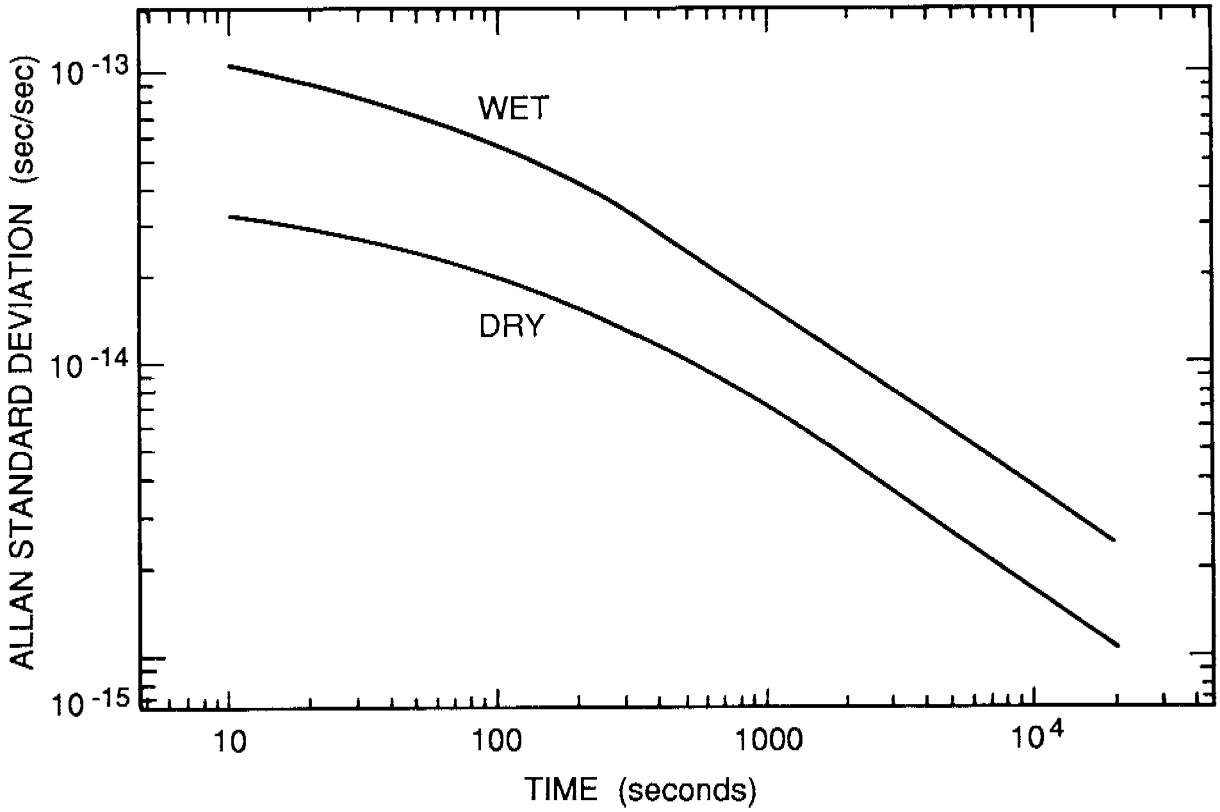

Figure 1: The calculated Allan standard deviation of the zenith wet and dry tropospheric delay.

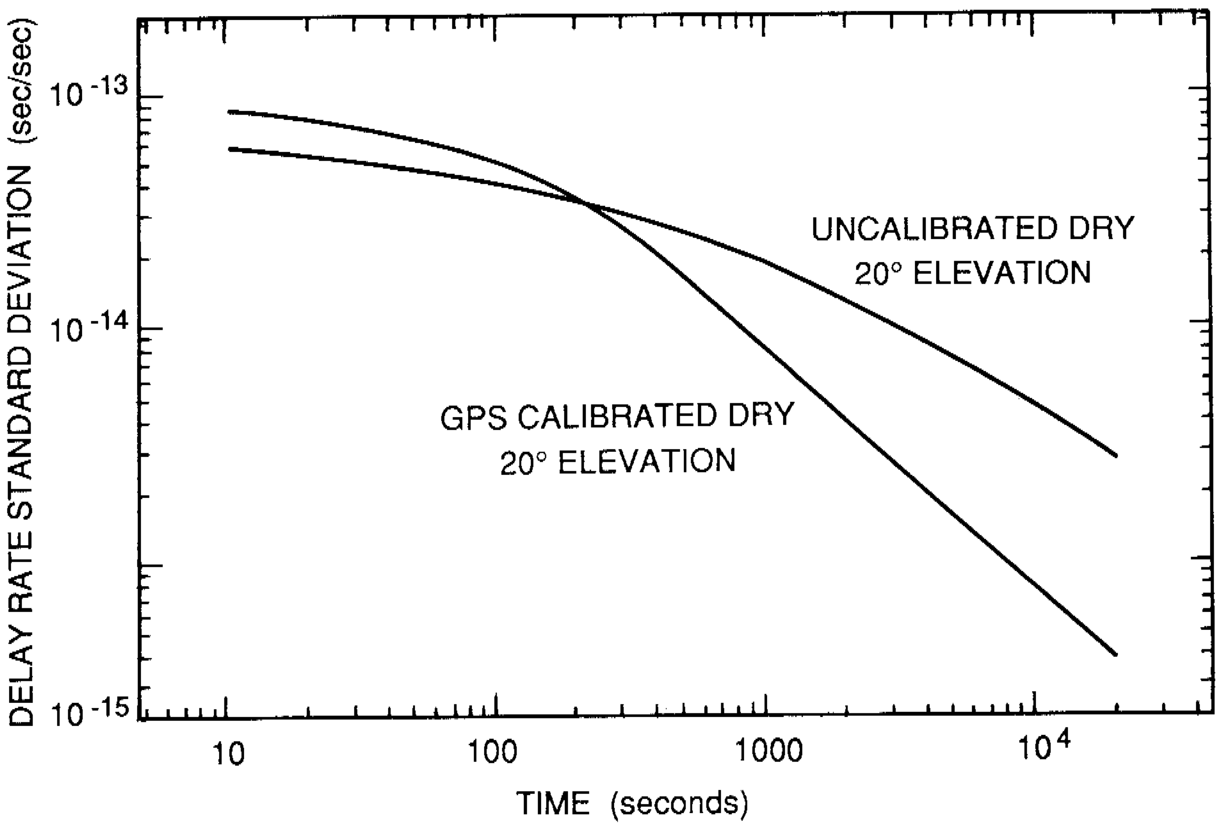

Figure 2: The calculated delay rate standard deviation of the 20-degree elevation dry troposphere. Also shown is the delay rate standard deviation for the difference between a 20-degree elevation raypath and a GPS raypath, also at 20 degrees elevation, and 20 degrees away in azimuth.

QUESTIONS AND ANSWERS

GERNOT WINKLER, USNO: In your first view graph, you showed the decreasing variation as a function of integration time. This cannot continue forever, do you have an idea where the turn–over point is?

MR. TREUHAFT: It is not so clear from the data the I have shown you here, but there is even a bit of a turn–over point in this plot. That is due to hitting the top of the atmosphere. There is another turn–over point which we base on a time series of WVR data as well as what people have said in the literature, and there is great debate on this. We believe that this turn–over point is of the order of thousands of kilometers, which means, in time, a good part of a day. Then it flattens out completely and is white from then on. That is of the order of 20,000 seconds.

HENRY FLIEGEL, AEROSPACE: I liked your paper very much and I have a very minor comment. You say that the solar hydrometer, in the traditional form, works only when aimed at the sun. There is no good reason, however, that it couldn't be made to work against the blue sky. Most of the blue sky light is, after all, coming from the oxygen and nitrogen in the atmosphere and the scale height of that is 18,000 feet, much higher than the scale height of water vapor. In principal at least you should be able to see the water vapor against the blue sky. Its just a question of engineering the hardware.

MR. TREUHAFT: It is just a matter of signal–to–noise at that point then?

MR. FLIEGEL: Perhaps so, but with photomultipliers there should be no difficulty with signal–to–noise. I am very happy that JPL is looking into the solar hydrometer, but maybe we should get rid of the word 'solar'. It is indeed a promising technique.